Timing Noise Properties of GRO J0422+32

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ABSTRACT

OSSE observed the hard X-ray transient source GRO J0422+32 (XN Per 92) between 11 Aug and 17 Sep 1992. High time resolution data were obtained over several energy bands in the ~35-600 keV range with timing resolutions of 8 ms and 125 μs. Power spectra at energies below 175 keV show substantial low-frequency red noise with a shoulder at a few 10^{-2} Hz, peaked noise with characteristic frequency near 0.2 Hz, and a second shoulder at a few Hz. The peaked noise profile is broad and asymmetric, with a sharp low-frequency edge and a high-frequency tail; thus the physical process responsible for the peaked noise appears to have a well-defined maximum timescale. The characteristic frequencies of the shoulders and the peak are independent of energy and source intensity. In addition, there is evidence for peaked components near 0.04 Hz and 0.1 Hz with variable intensity from day to day.

INTRODUCTION

The X-ray nova GRO J0422+32 (XN Per 1992) was discovered by the BATSE instrument on the Compton Gamma Ray Observatory in data from 5 Aug 1992 (Paciesas et al., 1992), and at its peak reached an intensity in soft γ rays approximately three times brighter than the Crab Nebula and pulsar. The source was declared a target of opportunity for GRO, allowing both OSSE and COMPTEL to view beginning 11 Aug 1992, approximately at the peak. With the exception of a 4-day break, OSSE observations continued for the following 37 days. The goals of the OSSE observations were threefold: first, to help localize the source; second, to provide detailed energy spectra above 50 keV, including a search for possible annihilation features, either red-shifted or blue-shifted; and third, to study the fast timing properties of the emission.

The results of scanning observations by OSSE were combined with occultation studies by BATSE to localize the source in an error circle with radius of 0.2 degrees (Harmon et al., 1992). An optical counterpart was proposed by Castro-Tirado et al. (1992) and confirmed by the soft γ-ray observations of SIGMA (Goldwurm et al., 1992). The nova shows no prior history of outbursts in the Harvard plates (Shao, 1992).

Energy spectra from OSSE are generally thermal in character and are reasonably well-described by an optically thin thermal bremsstrahlung functional form with temperature kT approximately 100 keV. The spectra are inconsistent with thermal Comptonization in an optically thick medium (Sunyaev and Titarchuk, 1980) at a single temperature. There is no evidence for persistent or time-variable annihilation radiation, whether narrow or shifted in energy and broadened. The characteristic temperature of the bremsstrahlung function increases (i.e., the spectrum hardens) as the source decays.

Timing analysis of the soft γ-ray data show significant red noise and peaked noise components (usually referred to as quasi-periodic oscillations, QPOs, in analogy with the narrow noise features in neutron-star binary systems). BATSE reported "QPOs" centered roughly at 0.04 Hz and 0.2 Hz (Kouveliotou et al., 1992), both of which were confirmed by SIGMA (Vikhlinin et al., 1992) and OSSE (Grove et al., 1992).

The hard spectrum, rapid variability, and lightcurve are similar to previous X-ray novae A0620-00 and XN Mus 1991, both of which have measured mass functions that make them very strong black hole candidates. By similarity of these features, GRO J0422+32 can be classified as a black hole candidate.

We report here on timing analysis of the extensive observations of GRO J0422+32 with OSSE. Details of the spectral analysis will appear elsewhere.

OBSERVATIONS AND ANALYSIS

OSSE observed GRO J0422+32 on 34 days spanning 11 Aug 1992 - 17 Sep 1992. The source reached its maximum intensity at 100 keV shortly after the start of the OSSE pointing, then began an exponential decline with a decay time of $\sim$40 days, falling to about half maximum intensity at 100 keV at the end of the pointing. The flux history from OSSE observations is shown in Figure 1.

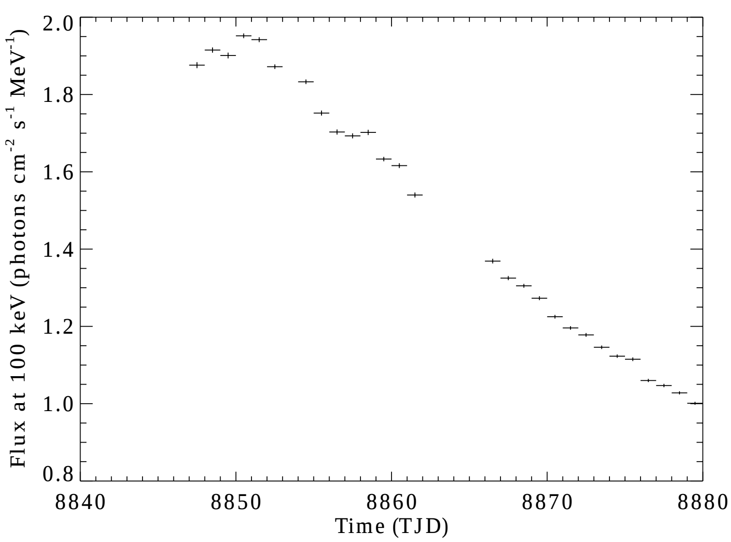

Figure 1: Lightcurve of GRO J0422+32 at 100 keV measured by OSSE.

OSSE observations consist of a sequence of $\sim$two-minute (i.e., 131.072 sec) measurements of a source field alternated with two-minute offset-pointed measurements of background; at any time two detectors are pointed at the source and two detectors are pointed away. High time-resolution data were collected from the on-source detectors in 8-ms rate samples in five energy bands from $\sim$35 keV to $\sim$600 keV. We formed the total power spectrum by Fourier transforming individual two-minute time series that contained no data gaps or dropouts, then summing these incoherently. This reduces potential systematic effects that might arise on long timescales from orbital variations in the background count rate or differences between source-pointed detectors.

DISCUSSION

Figure 2 shows the normalized power spectral density function in the 35-60 keV and 75-175 keV bands for the entire OSSE pointing. The function plotted represents the fractional root mean-squared (RMS) variation of the source intensity (I). The contribution from statistical noise has been subtracted. The total fractional RMS variation between 0.01 Hz and 60 Hz is $\sim$40% in 35-60 keV, and $\sim$30% in 75-175 keV. This is consistent with the large variation in X-rays reported by ROSAT (Pietsch et al., 1993). It is also consistent with the level reported in hard X-rays from Cyg X-1 (e.g., Miyamoto and Kitamoto, 1989); however it is significantly greater than that from neutron star binary systems, which typically have RMS/I $<$ 10% (although the Rapid Burster is a notable exception (Stella et al., 1988)). Evidently, the black hole candidates are noisier than accreting neutron stars.

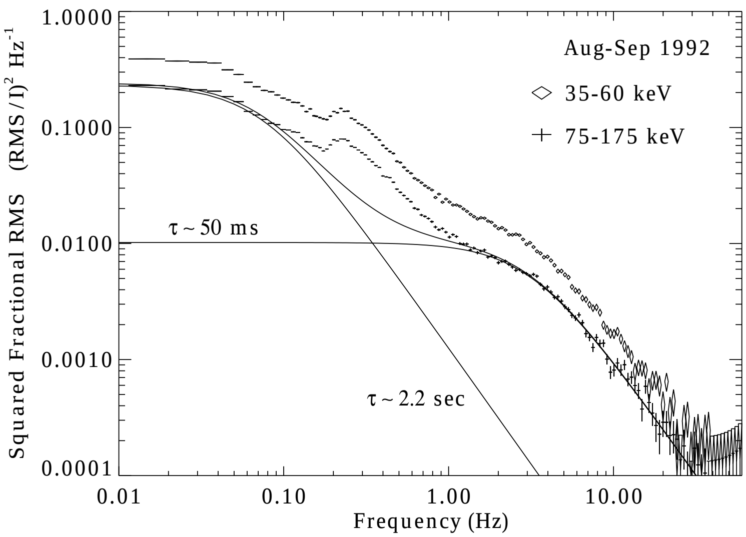

Figure 2: Normalized power spectra for GRO J0422+32 in 35-60 keV (upper) and 75-175 keV (lower) bands. Model fit (solid lines) to the 75-175 keV band includes exponential shots with lifetimes 50 ms and 2.2 sec.

The shape of the power spectrum is essentially identical in the two energy bands. It shows breaks at a few 10^{-2} Hz and a few Hz, and a strong peaked noise component (frequently labelled a QPO) at 0.23 Hz, with FWHM $\sim$ 0.2 Hz. Statistically significant red noise is detected at frequencies $>$ 20 Hz. Not readily apparent in this figure are intermittent peaked noise components at about 0.04 Hz and 0.1 Hz (see Figure 3). The amplitudes of these latter features vary from day to day.

Similar power spectra from black hole candidates have been modeled as a superposition of randomly occurring bursts, or "shots." If the shots have an instantaneous rise and exponential decay (or vice versa), the resulting power spectrum is constant below the characteristic frequency $1/(2\pi\tau)$ and falls as $1/f^2$ at high frequencies. This type of model can describe the two breaks and the $1/f^2$ behavior above several Hz in the power spectrum of GRO J0422+32 if there exist two shot components, with e-folding times $\tau \sim$ 50 ms and $\sim$ 2.2 sec. The power spectrum of both components and their sum are displayed in Figure 2. The sum may not be an adequate model of the continuum under the peaked noise component that dominates between 0.1 and 1.0 Hz, although without some physical motivation for the noise process it is difficult to judge. If instead the emission arises from shots with a distribution of lifetimes bounded by 50 ms and 2.2 sec, additional power would be produced in the region from 0.1 to 1.0 Hz. Indeed, if the lifetimes are distributed as $1/\tau^2$, the resulting power spectrum falls as $1/f$ between the frequencies corresponding to the bounding lifetimes (Halford, 1968; Shibazaki and Lamb, 1987). Although this particular distribution does not model the power spectrum of GRO J0422+32 very well—even ignoring the peaked noise—it does generally describe the EXOSAT power spectra of Cyg X-1 (Belloni and Hasinger, 1990). More modelling of the OSSE data are needed.

The profile of the peaked noise near 0.2 Hz is rather broad and asymmetric. Figure 3 shows the residual noise power assuming the two-shot model. Plausible alternative descriptions of the continuum between 0.1 and 1.0 Hz—e.g. a simple power-law interpolation with index -0.9—do not significantly alter the shape of the peaked noise, although they may change its amplitude. For the 75-175 keV band, the integrated fractional RMS variation between 0.1 and 1.0 Hz is about 18%, with the integral of the peaked noise component alone roughly 8-10%, depending on the continuum model. The peak shows a rather sharp cutoff below 0.2 Hz, suggesting that there is a well-defined maximum timescale associated with the underlying physical process, and a broad tail at frequencies above the peak. Such a peak profile cannot be described by a simple, symmetric Gaussian or Lorentzian. Peaks with a profile consistent with the average appear on each day of OSSE observation, with no significant evidence for variation in the frequency of the peak with flux. Thus if the asymmetry is due to a noise component that drifts in peak frequency, the timescale for the drift is much less than one day.

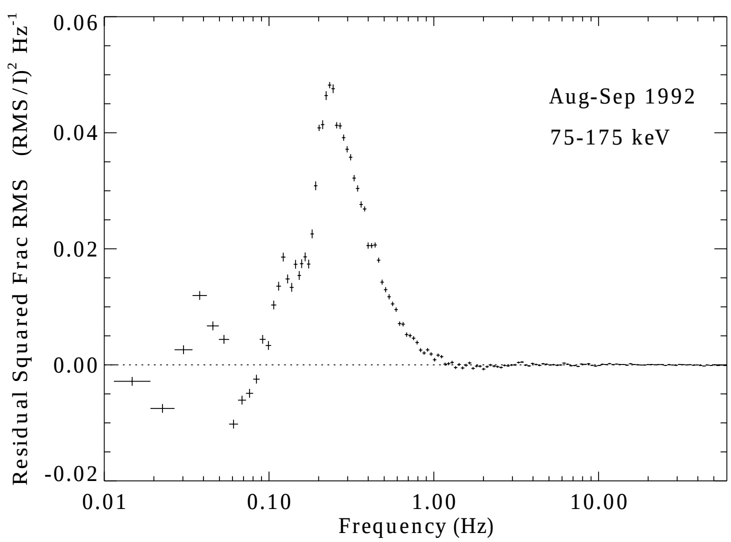

Figure 3: Residual noise power in the 75-175 keV band after the two-shot model spectrum is subtracted. Peaked noise components are visible near 0.04 Hz, 0.12 Hz, and 0.23 Hz.

The two-shot model also does not attempt to describe the peaked noise features apparent in the power spectrum near 0.04 Hz and 0.1 Hz. The lower frequency peak is the "QPO" first reported by BATSE (Kouveliotou et al., 1992). Both appear to be variable in amplitude on daily timescales, with some evidence for a variation in the frequency of the latter peak from day to day.

The integrated fractional RMS variation for frequencies between 0.01 Hz and 60 Hz changes as the intensity of the source decreases. Figure 4 shows the evolution of the fractional RMS, and comparison with Figure 1 reveals that it is anticorrelated with intensity; thus, as the source decays, the noise becomes a more significant portion of the total emission at these energies. Note, however, that the absolute RMS variation does indeed decrease with time; it merely decreases more slowly than the intensity. In addition, while the intensity in these energy bands drops by nearly a factor of two and the energy spectrum hardens over the course of the OSSE observation, the frequencies

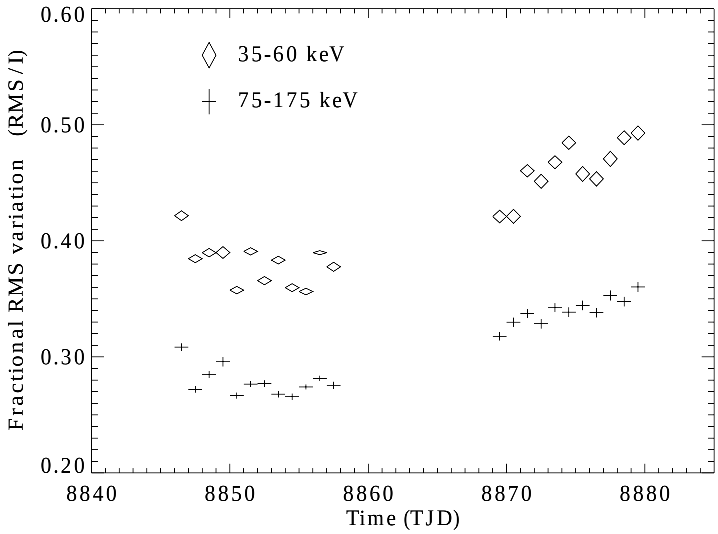

Figure 4: Evolution of the fractional RMS variation between 0.01 Hz and 60 Hz in the 35-60 keV (diamonds) and 75-175 keV (crosses) energy bands. The fractional RMS is anti-correlated with source intensity (see Figure 1).

of the two breaks and the main peaked noise remain constant: There is no evidence for significant variability in the timescales of the noise processes. This contrasts with Cyg X-1, where the X-ray power spectrum has a low-frequency break that varies by a factor of at least 10 with no apparent dependence on source flux (e.g., Belloni and Hasinger, 1990), and it contrasts with the QPO detected by Ginga in XN Mus 91 (Tanaka et al., 1991), which varied by a factor of $\sim$3 in frequency as the flux rose to maximum and then decayed away.

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